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Numerical investigation of the performance and hydrodynamics of a rotating tubular membrane used for liquid–liquid separation

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ABSTRACT

The performance of a liquid–liquid separation process based on an axially rotating tubular ceramic membrane operated in a crossflow regime is studied numerically with oil–water dispersions used as a model mixture. Internal hydrodynamics are explored using computational fluid dynamics simulations to obtain the velocity field in the continuous phase (water) and predict the separation efficiency with respect to the dispersed phase (oil). A discrete phase model is used to estimate trajectories of dispersed oil droplets within the membrane channel. The separation performance of the process is evaluated in terms of the droplet cutoff size. Effects of the Reynolds and Swirl numbers on velocity and pressure fields, shear stress, droplet cutoff size, and separation efficiency are investigated. The increased shear stress on the membrane surface due to the angular and the crossflow velocities decreased the accumulation of droplets on the membrane while increasing the separation efficiency. The droplet cutoff size is observed to decrease with an increase in the Reynolds and Swirl numbers. The separation efficiency strongly depends on the Swirl and Stokes numbers but only weekly on the Reynolds number. By increasing the Swirl number of the flow, it may be possible to remove very fine droplets by centrifugal force only and avoid membrane fouling.

1. Introduction

Crossflow filtration (CFF), also known as tangential flow filtration, is a membrane separation process wherein “the fluid on the upstream side of the membrane moves parallel to the membrane surface and the fluid on the downstream side of the membrane moves away from the membrane in the direction normal to the membrane surface” [1]. CFF finds broad applications in concentrating, purifying and stabilizing a variety of products [2]. Examples of CFF processes include desalination [3], wastewater treatment [4], juice making [5], wine and beer filtration [6,7] and blood purification [8].

A major challenge in membrane separation is membrane fouling. Fouling can dramatically reduce the permeate flux, shorten the life of the membrane and decrease the quality of the permeate [9]. The shear stress generated by the crossflow can reduce the accumulation of particles on the membrane surface [10]. CFF can possibly, depending on the system considered, have a steady-state operation. For solid–liquid separations, the thickness of the deposited layer on the membrane surface often increases with time so that permeate flux in CFF exhibits a time dependent behavior [11].

Membrane fouling can be mitigated by enhancing the shear associated with the axial flow with the shear due to the swirl as the swirling flow has an azimuthal component. This can be achieved with membrane rotation or by introducing the flow under an angle to induce swirl in a stationary membrane channel. The flow swirl also enhances the separation efficiency for mixtures involving droplets that are less dense than the continuous phase (e.g. oil droplets suspended in water) as the droplets migrate toward the core of a vortex due to centrifugal action. Previous research related to membrane filtration with rotational flows includes studies of rotating disk membrane separation [9,12–14], and flow through rotating porous annuli [15–18]. The dynamic crossflow filtration technique first proposed by Kroner et al. [19] was used for solid–liquid separation. Their system consisted of two co-axial cylinders: the inner cylinder was rotated whereas the outer cylinder was a stationary membrane. They observed that the crossflow linearly increased with rotational speed and that membrane fouling was reduced due to an increase of the wall shear stress at the inner cylinder. Liebermann [14] mentioned that a combination of centrifugal and shear forces in dynamic crossflow filtration improves control over the fouling of a membrane surface. The overarching observation is that rotational CFF systems have the advantage of a substantially improved filtration performance

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due to the rotation-induced mitigation of membrane fouling [20]. To our knowledge the only studies on the application of rotating membrane systems to liquid–liquid separation are those by Ji et al. [21] and Gorobets at al. [22]. Advanced numerical studies should be helpful for understanding critical aspects of the process and potentially guiding and optimizing the design of such filtration systems.

Numerous challenges are related to cleaning of produced water. Oil droplets dispersed in the produced water are small (droplet size normally ranges from less than 1 μm to 50 μm) [23], and density difference between the two phases is typically less than 150 kg/m^3 [24,25]. Such dispersions are hard to separate using conventional swirl generators (e.g., hydrocyclones), flotation vessels or centrifugal separators [26]. In that case a rotating membrane system can play an important role in cleaning produced water or separating other dispersions characterized by small droplet size and a low density difference.

This work deals with the separation of liquid–liquid dispersions by a rotating tubular membrane. Flow patterns, permeate flux, shear stresses at the membrane surface, and separation efficiency are studied by solving numerically the Navier–Stokes equations using Ansys Fluent 14.5. The effects of the Swirl and Reynolds numbers on flow patterns, droplet cutoff size, and separation efficiency are elucidated and interpreted in terms of their implications for membrane performance.

2. Geometry and test cases

The rotating CFF system studied in the following simulation corresponds to a tubular microfiltration membrane. The geometry of the CFF system is shown in Fig. 1. The CFF system has a membrane that rotates about the longitudinal z-axis with an angular velocity ω. The membrane has a thickness (δ) of 2 mm and a length (L) of 250 mm mimicking the physical dimension of ceramic membranes manufactured by TAMI Industries. The inner diameter (D) and the permeability (α) of the membrane are 6 mm and 1×10^{-14} m^2 (10 millidarcy) respectively. The permeability is the proportionality constant in the expression for volumetric permeate flux ($\overline{U}=J=\alpha\Delta P/\mu\delta$), which relates permeate flux (J) and fluid viscosity (μ) to a pressure differential (ΔP) across the membrane. The value of the permeability in the simulation is selected to match the value experimentally measured in our laboratory [27]. A fully developed Hagen–Poiseuille laminar flow is defined as the inlet condition. Simulations are performed for three different swirl numbers (S_w) and three different Reynolds numbers (Re) as shown in Table 1. The inlet Reynolds number is defined, based on the cylindrical geometry of the membrane, as $Re=4\dot{m}_w/(\pi\mu_w D)$ where $\dot{m}_w$ is the mass flow rate at the inlet and μ_w represents the viscosity of water.

The swirl intensity of a flow field can be characterized by the Swirl number (S_w), which is defined as

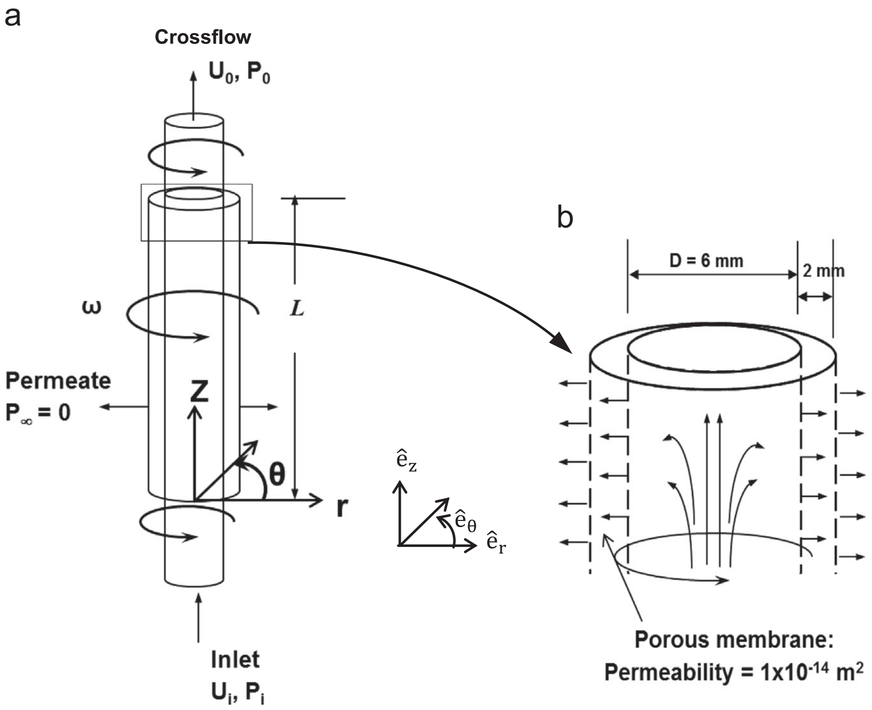

Fig. 1. (a) Illustration of the geometry of a crossflow filtration system wherein the microfiltration membrane is rotating about the vertical axis with an angular velocity of ω; (b) view of the membrane defined by a square box shown in (a). Arrows are used to represent the flow in the axial, radial and azimuthal directions.

Table 1
Parameters used in simulation test cases. Cases 1–5 correspond to a non-turbulent flow regime (Re < 2300) and Case 6 to a transitional flow regime (2300 < Re < 4000) [28].

Cases	N angular velocity of the membrane (rpm)	Q_i flow rate at inlet (m^3/s)	S_w Swirl number $S_w=\omega R/\overline{U}_z$	Re Reynolds number $Re=4\dot{m}_w/(\pi\mu_w D)$
1	0	6.67×10^{-6}	0	1415
2	500	6.67×10^{-6}	0.75	1415
3	1000	6.67×10^{-6}	1.50	1415
4	1500	6.67×10^{-6}	2.25	1415
5	1500	1.00×10^{-5}	1.50	2122
6	1500	1.33×10^{-5}	1.10	2822